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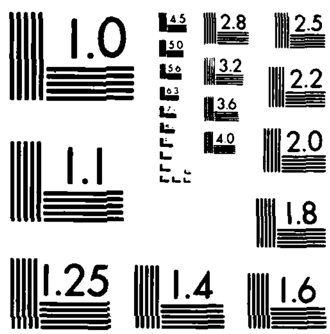

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ELECTROMAGNETIC INSPECTION OF WIRE ROPES USING SENSOR ARRAYS

Herbert R. Weischedel
NDT Technologies, Inc.
P.O.Box 637
150 Strong Road
South Windsor, CT 06074

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Quarterly Progress Report for Period
16 December 1984 - 15 March 1985

Prepared for

OFFICE OF NAVAL RESEARCH
DEPARTMENT OF THE NAVY
800 N. Quincy Street
Arlington, Virginia 22217

QUARTERLY PROGRESS REPORT

16 December 1984 - 15 March 1985

Summary

In the time period between 16 December 1984 and 15 March 1985, we achieved the following:

- We improved our prototype instrumentation and procedure for the inspection of wire rope end sections. Laboratory experiments clearly demonstrate the viability of this approach; however, a considerable amount of field testing and further development will be required to make this procedure sufficiently rugged and reliable under adverse field conditions.

The following is a summary of the additional development work necessary to make end section inspections a useful in-service inspection procedure:

- Develop bigger instruments to accommodate prevalent rope and socket sizes.

- Reconfigure signal acquisition and processing system to make it portable and sufficiently rugged for field use.

- Redesign and extend signal conditioning software to make it usable for relatively unskilled personnel.

- Redesign optical position transducer to increase its resolving power.

o Perform extensive field testing to eliminate unexpected problems and to establish credibility of the new procedure and to make end section inspection an accepted and viable in-service inspection method.

o We developed and manufactured a new mechanical rope position transducer. As compared to our previous designs, the new transducer is drastically simplified and ruggedized.

INSTRUMENT FOR THE INSPECTION OF WIRE ROPE END SECTIONS.

1. Identification and Significance of the Problem

During operation, moving and standing wire ropes are subjected to, sometimes severe, vibrations which excite longitudinal, lateral and torsional rope oscillations. For all types of rope oscillations, longitudinal, lateral or torsional, rope terminations constitute oscillation nodes, causing a major part of the oscillatory energy in the rope to be absorbed by the end attachment.

Rope oscillations induce considerable tension, bending and torsional stresses at the rope terminations which cause the wires to fatigue and, eventually, to break. Wires can break internally and externally. Furthermore, wire breaks can occur inside the socket entrance where detection is difficult if not impossible. Wire fatigue, particularly at the nose of the socket, frequently causes early failure and maintenance problems. Rope breakage at the end attachments is a common failure mode, which makes rope terminations a critical area in assessing a rope's condition.

A typical form of vibrational fatigue occurs in installations which are subject to cyclic loading, for instance boom suspension systems of draglines. Here, the vibrational energy, induced by cyclical loading of the rope, is absorbed at the end fittings of the pendants causing eventual fatigue breakage at this point.

Another example: Normal operation of a machine or hoist induces oscillations. For instance, in shaft hoists, start up of the cage at

the bottom excites low frequency oscillations in the rope. As the cage reaches the top of the shaft, the free length of rope becomes shorter and the initial slow oscillation turns into a high-frequency vibration. A major part of the vibrational energy is dissipated in the cage attachment, resulting in eventual fatigue breakage of the wires at the attachment of the cage.

Corrosion can also cause rope deterioration inside the socket. For instance, acid is often used to etch the wires before zinc socketing. If the wires are not carefully cleaned after the etching, the left-over acid can cause corrosion inside the socket. Another example: For some marine applications, end attachments are frequently submerged in sea water which causes corrosion inside the socket where detection is difficult.

2. Technical Approach and Present Status of Research and Development

In the past, none of the available NDI instruments was, even remotely, useful for the inspection of wire rope end terminations. One of the objectives of the present R&D effort is to remedy this situation, and to develop instrumentation and a procedure for the inspection of wire rope end sections.

As part of the present SBIR Phase II research, we implemented prototype instrumentation for the inspection of wire rope end terminations. We designed, manufactured and evaluated an "end section coil" which can be attached to a regular instrument as shown in Figure 1. This arrangement has the advantage that the inspection

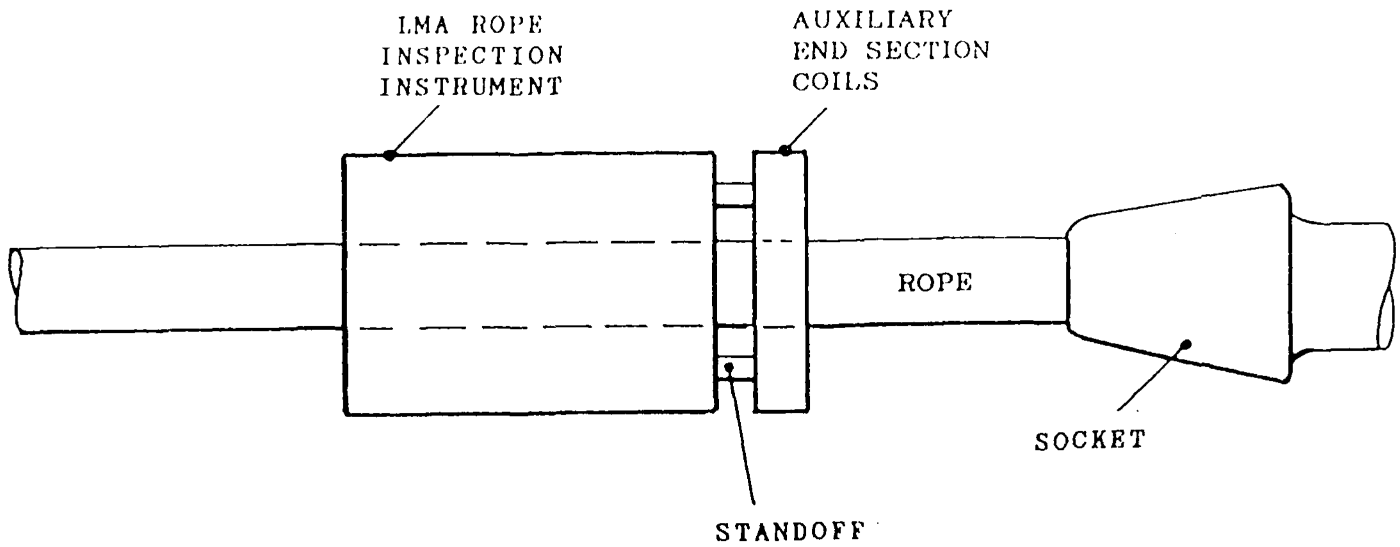

Figure 1: Instrument for the Inspection of Wire Rope End Sections

instrument can be used for regular inspections and, in combination with the end coil attachment, for end section inspections.

Technical Approach

Close to the end termination, the socket grossly distorts the magnetic field. As expected, experiments indicated that the greatly distorted magnetic field close to the rope termination socket can conceal the relatively small distortions of the magnetic field caused by defects. The minute defect signals, superimposed on the signals caused by the distorted field, are hard to identify and evaluate.

Because of this problem, the determination of defects ultimately has to be based on a comparison of subsequent inspection results, and a basic inspection program of the following type should be implemented:

1. To establish baseline data for subsequent inspections, the program has to be initiated by a first inspection of the new rope including end termination after its installation and after a sufficient break-in period. This baseline inspection yields the "***Reference Signal.***" Note that the acquisition of separate Reference Signals for each individual rope termination is probably not necessary. A single Reference Signal, useful for all rope terminations of identical design, should be sufficient.

2. Successive periodic inspections are performed at predetermined intervals. These inspections yield the "***Test Signal.***"

3. All inspection results are compared with the results of the baseline inspection. Defects will be indicated by deviations of the *Test Signal* from the *Reference Signal*.

Since the magnetic field in the rope is drastically distorted by the rope termination, defects are indicated by relatively minuscule deviations of the *Test Signal* from the *Reference Signal*. Therefore, to allow a reliable and accurate comparison of successive test results, the following two conditions have to be satisfied by the test instrumentation:

1. **Test results must be reproducible with extraordinary accuracy and reliability**, and

2. **the comparison of test results has to be performed with great accuracy and resolution.**

In particular, to make test results reproducible, the following conditions must be satisfied:

- **Test results must be completely independent of the azimuthal position of the instrument with respect to the rope.**

  Because the magnetizer assembly as well as the attached end section coils have almost perfect rotational symmetry, this condition is satisfied for our bigger prototype instruments.

  Note that rotational symmetry is hard to achieve for instruments which use discrete sensors, such as Hall Generators or Flux Gate

Sensors, for magnetic field sensing.

- **Test signal amplitudes must be independent of rope speed.**

  Because our sensor design uses sense coils together with signal integration, this condition is automatically satisfied for both, the LMA and the LF signal.

- **The position of the test signal with respect to the rope longitudinal axis must be determined with great accuracy and resolution.**

  Our incremental optical encoder was modified to allow position sensing with a resolution of approximately 0.047". This resolution is sufficient to achieve the required repeatability of the test results.

- **The magnetic state of the rope including the socket, prior to the test, must be accurately reproducible to avoid a distortion of the defect signal due to the remagnetization effect.**

  Problems caused by remagnetization of the rope can be avoided by magnetically homogenizing the rope before the inspection. Homogenization is achieved by simply moving the rope through the instrument once before the inspection.

  The socket, which is made from steel, could also become permanently magnetized in a random fashion. Although, in our lab experiments, we were not able to produce any artificial random

magnetization of the socket which produced deterioration of the test results, problems of this type are conceivable.

To allow an accurate comparison of test results obtained from different inspections, our data acquisition system, comprising an IBM PC XT computer including analog/digital interface circuitry, is well suited. Figure 2 shows a functional block diagram of the arrangement which was used for our lab experiments. The following procedure was used:

1. To keep the rope and socket in a centered position with respect to the instrument, the following mechanical arrangement is used:

   A guide sleeve made from UHMW polyethylene is first mounted on the rope and on the socket as indicated in Figure 2. For easy mounting in the field, the guide sleeve is subdivided. The instrument, with the end section coil and position transducer (incremental encoder) attached, is then mounted on the guide sleeve and the rope as shown in Figure 2, with the end section coil facing toward the rope socket. The instrument assembly can be moved in the longitudinal direction on the rope. Note that the sleeve is tightly fit to the socket in such a fashion that, as the instrument assembly moves away from the socket, the sleeve first stays stationary with respect to the socket. The magnetizer including the sense coil first moves on the guide sleeve until it reaches the flange of the guide sleeve. Then the guide sleeve moves with the instrument assembly over the rope in the longitudinal direction.

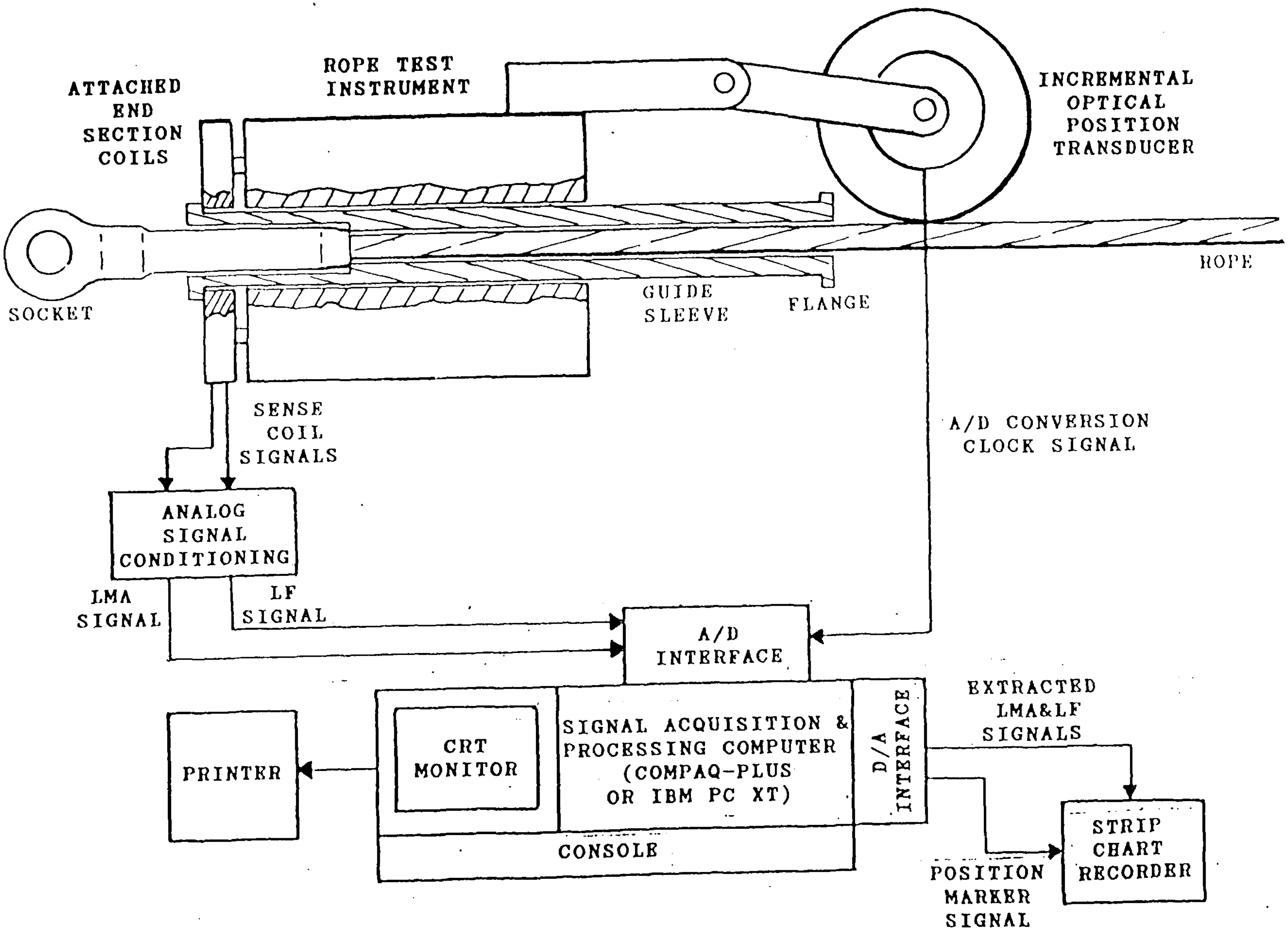

Figure 2: End Section Inspection System

2. To magnetically homogenize the rope, the instrument is moved toward the socket and beyond the end of the socket as far as possible. Note that the inner coil diameter and the inner magnetizer diameter are larger than the diameter of the socket, and the end section coil can be moved approximately 6" beyond the end of the socket. To magnetically homogenize the rope including the socket, the instrument is moved approximately 6 feet away from the socket and is then returned to its original position on the socket. The rope including the socket is now magnetically homogenized and in a well defined magnetic state.

3. The data acquisition system is set up and programmed in such a fashion that the sampling of data points is clocked by pulses from the incremental encoder at a sampling rate of approximately 21 samples/inch. This approach, together with the previously discussed procedures, makes data acquisition independent of time and completely reproducible.

4. The computer data acquisition program is now started.

5. The instrument is manually moved away from the rope socket. As the instrument moves, the incremental encoder produces pulses at a rate of approximately 21 pulses/inch. Each pulse triggers sampling of one data point. The sampled test data points are stored on hard disk.

6. To initiate the lab experiments, an inspection of the sample rope, including socket, in its original condition is performed. These inspection results are stored on disk and serve as the

Reference Signal.

7. Defects are simulated by attaching short pieces of wire to the rope. Then, to obtain the ***Test Signal***, the above test procedure is repeated for the rope with these simulated rope flaws. The ***Test Signal*** is stored in the computer on disk.

8. A separate computer program compares the ***Reference Signal*** with the *Test Signal*. Since bo signals are reproducible with considerable accuracy and reso n, this can be accomplished by simply ubtracting correspondi store a points of the two signals.

Test Results

Figure 3 shows test results obtained from an end section inspection of a 3/4" IWRC rope using an LMA-175 instrument including an end section coil and an incremental optical encoder. The experiment was performed according to the above procedure.

The ***Reference Signal*** was acquired and stored on disk by inspecting the rope close to the end section in its original condition. To simulate a rope flaw, an 8 inch long wire with a metallic cross-sectional area of approximately 1.2% of the total rope cross-sectional area was attached to the rope with one wire end tucked under the socket for approximately 1". With this wire attached, the rope was then inspected and the ***Test Signal*** was also stored on disk. The location of the attached wire is indicated in the figure.

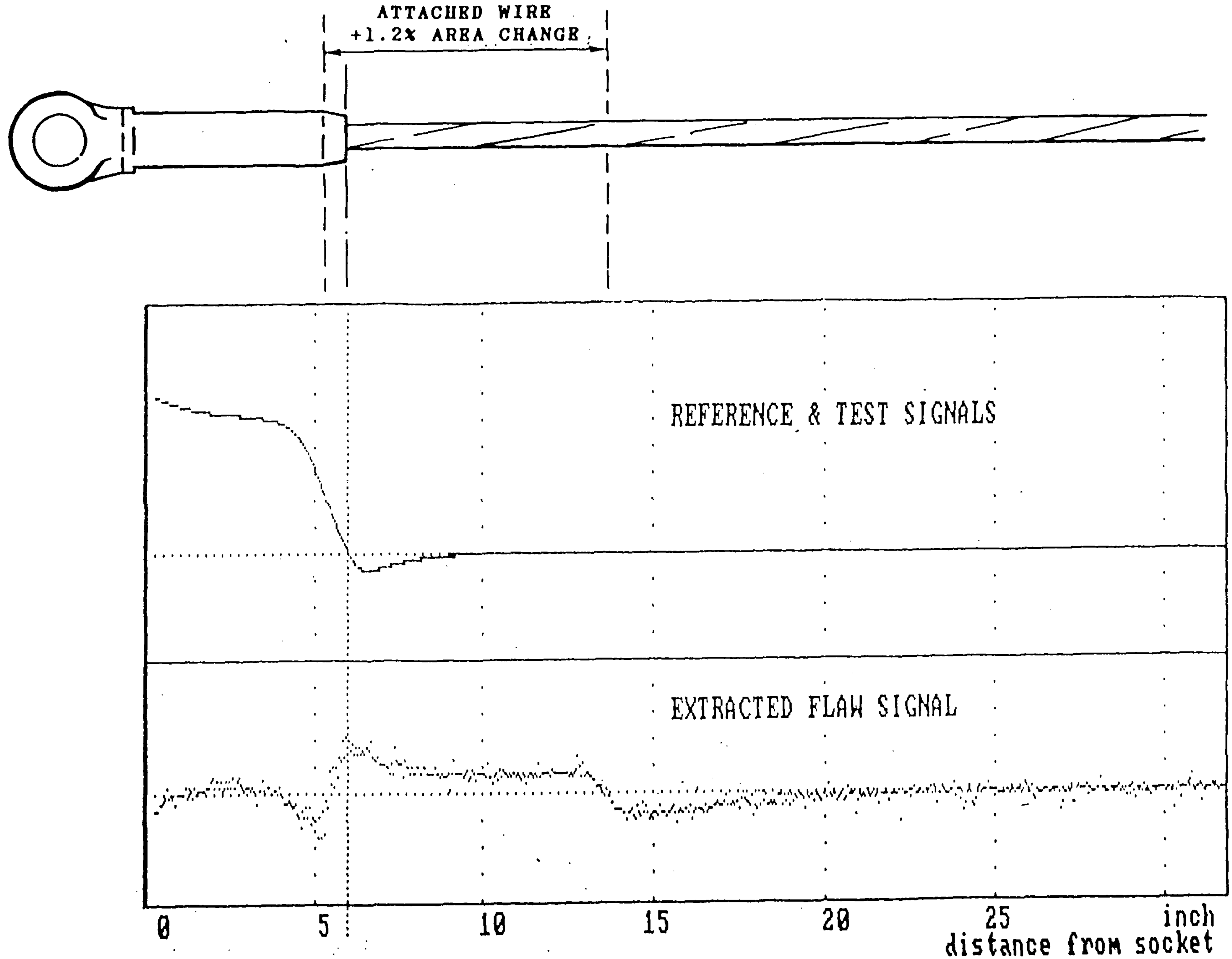

Figure 3: End Section Inspection - Experimental Results

The upper part of Figure 3 shows the ***Reference Signal*** and the ***Test Signal***. Caused by the socket and the rope end, the ***Reference*** and ***Test Signals*** are greatly distorted. Note that, within the resolution of the computer printout, the ***Reference Signal*** and ***Test Signal*** are almost indistinguishable.

Using the computer, the flaw signal was then extracted from both signals by subtracting the ***Reference Signal*** from the ***Test Signal***. The extracted flaw signal is shown in the lower part of Figure 3.

Close to the rope terminations, even small deviations of the relative position of the two signals can cause drastic inaccuracies in the extracted flaw signal. Therefore, the computer program allows for a micro-adjustment of the absolute position of both signals by plus or minus one sample point (equivalent to a distance of +-0.047 inches). The adjustment is accomplished by interpolation. At this stage of the research, the position micro-adjustment is performed automatically by a simple computer optimization algorithm.

In Figure 3, the LMA signal is slightly deformed as compared to the shape of the LMA signal caused by the same flaw in an instrument with our regular symmetrical sensor-magnetizer arrangement. A computer simulation shows this deformation to be caused by the unsymmetrical coil-magnetizer geometry. Since the phenomenon is well understood, a computer algorithm could conceivably be designed to eliminate this distortion.

From this example we can draw the following conclusion: A 1.2%

cross-sectional area change can be clearly detected. Since in actual rope applications area changes of 10% or more are of concern, the present end section inspection method offers a comfortable error safety margin, and the method appears clearly feasible.

Data Acquisition System

For our laboratory experiments, we use an IBM PC XT Personal Computer together with Data Translation analog-digital interface hardware to implement a test system as shown in Figure 2. Unfortunately, this test set-up is not portable and therefore not suitable for field testing.

However, ruggedized portable computers, suitable for data acquisition and processing applications, are now available. They can be used, on-site, for in-service end-section inspections. An on-site data acquisition and processing computer has the advantage that test results can be immediately evaluated. Any doubts or discrepancies concerning the test results can then be directly investigated and resolved on-site.

A portable COMPAQ-Plus Personal Computer would be well suited for our data acquisition applications. This portable computer is completely equivalent to the IBM PC XT and compatible with our present Data Translation data acquisition system. The COMPAQ computer has only two minor drawbacks: It is not battery operated and requires an electrical outlet which might cause some inconvenience under certain field conditions, and, although portable and rugged, it appears primarily intended for office use. Alternate ruggedized IBM

PC compatible computers, designed for military and other field applications, will undoubtedly become available in the near future. These computers can then be easily adapted for wire rope inspections.

3. Further Development

Although feasibility of the end section inspection method has been demonstrated by lab experiments, a considerable amount of field testing and further development will be required to make this procedure sufficiently rugged and reliable under adverse field conditions.

Field Testing.

Field testing of our newly developed instruments has been difficult for us in the past. It is absolutely necessary because of the following reasons:

- Most of our experiments are performed in the lab under well controlled conditions. While these lab tests are indispensable for instrument development, they are often not a true reflection of instrument performance under actual and usually adverse field conditions.

We and some of our customers have encountered, in the past, some unexpected problems when our instruments were first exposed to field conditions. Our more experienced and sophisticated customers have reported these problems back to us, and we were usually able to correct them.

o For most of our potential customers, nondestructive wire rope inspection is a brand new development. Therefore, they are very skeptical and insecure as far as this type of instrumentation is concerned. Especially the suggested use of a computer for rope end section inspections might cause significant problems and anxiety for less sophisticated potential customers. Field evaluation of our instruments would greatly alleviate this skepticism. It would add a measure of credibility, which will be necessary for successful marketing of our instruments.

The design of our LMA instruments could build on the extensively published field experience with nondestructive rope inspection which was accumulated over a time period of several decades. If nothing else, this experience demonstrated that nondestructive wire rope inspection is feasible.

Our End Section Inspection System, however, is a completely new development, and no previous field experience with this type of inspection is available, anywhere. To make End Section Inspection, now in its infancy, a viable and accepted inspection procedure will require extensive field testing, combined with additional development work. For instance, end section inspections rely on an extremely accurate repeatability of test results. Therefore, the question of repeatability of test results under adverse field conditions is crucial and must be resolved.

Additional Development

To make end section inspections a viable in-service inspection procedure, the following further development work will be necessary in addition to an extensive field testing program:

Development of larger instruments. Since end sockets are considerably larger than the attached rope, the size of the inspection instrument has to be significantly increased for end inspections. The largest instrument presently available to us is useful for inspecting sockets up to 2 1/2" diameter, corresponding to rope diameters up to approximately 1". This is clearly not sufficient for inspecting all ropes presently used by the US Navy. Larger instruments, including the corresponding end section coils, would have to be designed and manufactured. Since the weight and size of instruments increases approximately as the 2.5th power of the socket diameter, the design and manufacture of larger instruments poses considerable mechanical problems.

Redesign optical position transducer. Our present position transducer has a resolution of approximately 0.047" which is sufficient for our lab experiments. However, it would be desirable to "oversample" data points. The excess data can then be used for digital filtering which would increase testing accuracy. Therefore, a position transducer with increased resolving power should be designed and manufactured.

Reconfigure signal acquisition and processing system. Our present system must be reconfigured and repackaged by using a portable COMPAQ-Plus or equivalent fieldworthy computer.

Redesign and extend signal conditioning software. The present signal processing software is primarily intended for our lab experiments. Its operation requires considerable skill. The software should be streamlined to make it usable by less experienced personnel. The evaluation programs could be made self-prompting and menu-driven, which would make their use extremely simple.

Several automatic filter and deconvolution algorithm should be developed to make the evaluation of test results automatic and foolproof. The present optimization procedure for aligning test signals should be improved.

SIMPLIFIED ROPE POSITION TRANSDUCER.

We designed, manufactured and evaluated a simplified rope distance counter. The new rope distance transducers, using permanent magnets and sense coils, are drastically simpler than our previous position transducer designs which incorporate an optical encoder.

The design of the new distance counter is very simple. Small permanent ferrite magnets are embedded into the body of a rubber wheel. The rope drives the wheel. The moving magnets induce pulses in two sense coils as the wheel moves. The coils are positioned in a quadrature arrangement which, by using simple logic circuitry, allows direction sensing. The rope position is determined by counting the induced pulses in an up-down counter.

The new position transducer is drastically simpler and more rugged

than our previous designs which use an optical encoder. Another advantage of the new transducer is that it uses only passive components such as permanent magnets and coils which do not require a power supply. For instance, the new transducer could easily be adapted for underwater operation.

Note, however, that the resolution of the new transducer is only approximately 0.2 inches. Therefore, for end section inspections our previous optical position transducers with their much better resolution will still be required.

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